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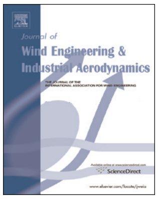

Numerical and experimental methods to investigate the behaviour of vertical-axis wind turbines with stators

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ABSTRACT

The practice of reproducing wind tunnel tests by means of CFD numerical simulations, which is known as numerical wind tunnel (NWT), is becoming quite common in many research fields of wind engineering. Wind tunnel tests can provide the indispensable validation data needed for CFD numerical simulations; at the same time, CFD can be considered a complementary support for wind tunnel tests in order to obtain a more comprehensive description of the flow field. In the present paper, NWT technique is applied to study the flow around and inside a multi-stage vertical-axis wind turbine (VAWT) surrounded by stator vanes. At first, the flow field has been studied in the wind tunnel by means of experimental tests. Then the experimental results have been used to validate a CFD model. The numerical model has finally been used to study and describe how the results obtained by means of the physical model can be extended to more general conditions.

1. Introduction

In the last decades, because of lagging in the sources of conventional fuels, a great effort has been made to improve the efficiency of renewable energy sources. Among them, both horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT) experienced a very fast development. In particular, small-size wind turbines seem very promising for decentralised power generation (Conejo et al., 2011). This is due to the fact that they have a low environmental impact, they do not cause instabilities in the power network distribution, and they do not need large power storage capabilities (e.g. Beller, 2009; Mertens, 2006). Besides, in very complex contexts, VAWT have some advantages with respect to HAWT, like the independency on the direction of the incoming flow (Balduzzi et al., 2012) and their simpler and cheaper construction and maintenance.

VAWTs appear to be particularly promising for conditions corresponding to low wind speed and urban areas, even if they suffer from a poorer efficiency with respect to HAWTs. However, as stated by Akwa et al. (2012), rotor performance is affected by operational conditions, geometric and air flow parameters, and all of these variables can be changed to improve the performance of VAWTs. For instance, Fujisawa (1996) studied the effects of different overlap ratios on the flow fields in and around a Savonius rotor through particle imaging velocimetry; Saha et al. (2008) conducted wind tunnel tests to evaluate the aerodynamics performance of different rotors in order to optimise the number of stages, and the number and the geometry of the blades; Howell et al. (2010) tested the effect of different surface roughness of the rotor blades on the turbine's performance.

Apart from the rotor design optimisation, Akwa et al. (2012) report that performance gains of up to 50% can be reached with the use of stators. At the authors' knowledge, one of the first studies focusing on this subject dates back to 1978, when Alexander and Holownia (1978) published an experimental research on a Savonius rotor, testing in wind tunnel the effects of geometry (blade aspect ratio, blade overlap and gap) as well as the effects of different stators (end plates and shielding obstacles) on the air flow. More recently, Mohamed et al. (2011) have shown numerically that it is possible to obtain performance gains of around 30% using an obstacle plate ahead of a Savonius rotor. They also provide a brief review on the use of stators around this kind of rotors, reporting for example the work done by Irabu and Roy (2007) using a guide-box tunnel, and by Altan et al. (2008) using a frontal nozzle. Note, however, that the adoption of stators to increase the performance of wind turbines can be considered a strategy that applies independently on the rotor type, as shown for example by Pope et al. (2010) and Chong et al. (2013), who report the role of stator vanes in increasing turbine performance for VAWTs with non-Savonius rotor types.

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Nowadays, the investigations aimed at evaluating the behaviour of wind turbines are generally carried out in wind tunnels or numerically. As far as the Savonius VAWT is concerned, a wide list of reference can be found in Roy and Saha (2013a, 2013b). Both methods have strengths and weaknesses. On one hand, tests carried out in wind tunnels have to face with blockage (see Ross and Altman (2011), for a review) and scale problems. On the other hand, the use of CFD has to deal with very high time-consuming computations where flow separation plays an important role, as well as with uncertainties due to the specific characteristics of the numerical model adopted, such as its physical formulation, mesh resolution and geometry, inlet and boundary conditions, turbulence model, etc. Both these aspects make this kind of calculation very difficult (Roache, 1997; Mohamed et al., 2011). Consequently, results of both experimental and numerical methods might lead to not negligible errors.

In the last years, the comparison of numerical simulations and wind tunnel data has become a common practice to take advantage from both tools and obtain more reliable results. Wind tunnel tests provide the indispensable validation data needed for the CFD numerical simulations; at the same time, the latter can be a complementary support for the wind tunnel tests in order to provide the whole flow field data for certain parameters (Blocken, 2014). Castro and Graham (1999) have defined the practice of reproducing the wind tunnel tests by means of CFD numerical simulations as numerical wind tunnel (NWT). Moonen et al. (2006) and Calautit et al. (2014) have applied the CFD to simulate the flow conditions in the whole closed-loop circuit of their wind tunnels. However, because of the computational burden required, only the wind tunnel test section is usually considered when dealing with CFD simulations.

Following the NWT concept, the present paper deals with the evaluation of how the flow field is modified due to the presence of stators in a multi-stage VAWT. In this kind of wind turbine, the flow field is very complex. Assuming a two-dimensional incoming wind field, the rotor stages in the middle of the wind turbine may experience an almost two-dimensional flow, as the air cannot go above or below them. At the top and bottom stages, instead, the flow is three-dimensional and speed-ups can occur above or below them, respectively. The role of stator vanes can be very important in order to enhance the air convergence through the gaps between stator elements, avoiding speed-up effects above or below the stages. The problem of representing properly two- or three-dimensional flows around the turbine in the wind tunnel is investigated numerically in order to identify the main geometrical constraints that should be adopted to make the experimental results reliable and to limit errors in the turbine's performance evaluations. It is also timely to point out that VAWT are usually immersed in a complex atmospheric boundary layer, because they are generally quite close to the ground. Such an aspect implies that turbine stages at different heights above the ground can undergo very different incoming wind profiles, depending for instance on the terrain roughness upwind, atmospheric stability conditions, wind velocity aloft, topography, etc. A homogeneous incoming wind field has been chosen here, however, in order to study a very general case. The actual wind turbine behaviour under non-uniform inflow conditions is not predictable a priori and it has to be related to the real conditions surrounding it and studied on a case-by-case basis.

The whole study was organised in two different steps. In the first step, a physical scaled model of the complete wind turbine with rotor and stators has been realized. The rotor was not considered, however, for testing the turbine's aerodynamics, because the prototype's behaviour under real operational conditions has not been investigated yet. Therefore, the aerodynamic effects of the stators without rotor have been evaluated by means of wind tunnel experiments, as described in Section 2.

In the second step, the role and the effects of the geometrical scale of the physical model in conditioning the experimental results obtained in the wind tunnel have been investigated through CFD numerical simulations. Firstly, the numerical simulations have been validated with respect to the wind tunnel measurements. Then, nine reduced-scale models and five enlarged-scale models with respect to the initial scale have been tested at a fixed inflow wind speed and direction (with respect to the stators orientation), in order to quantify the possible blockage effects and mutual interactions between walls of the test section and physical model. All the performed numerical simulations are described in Section 3.

The validation of the numerical model with respect to wind tunnel measurements and a critical discussion about the geometrical scale that has turned out to be the most proper to represent two- and three-dimensional air flows around obstacles in the wind tunnel are reported in Section 4. Finally, the main conclusions are summarised in Section 5.

2. Wind tunnel experimental set-up

The experimental tests have been performed on a single stage of the three-blade Savonius VAWT shown in Fig. 1(a). This is a prototype designed by Elkrom Ltd., which is 3000 mm tall at full-scale. It is equipped by three stators inscribed within two circumferences of $R_i = 2$ m and $R_e = 3.6$ m centred with respect to the rotation axis. Both blades and stators are equally spaced of 120°. Stators cannot be oriented with respect to the incoming wind direction.

The final VAWT is supposed to consist of several rotor stages piled on each other, eventually with the lowest one not directly on the ground if the wind turbine is going to be mounted on a tower. In this configuration, the flow around the stages close to the top and the bottom of the array is expected to be strongly three-dimensional, with speed-up effects above or below them. On the contrary, depending on their number and the resulting slenderness ratio, intermediate stages could experience quasi-two-dimensional flows that, in principle, should also increase the stators efficiency (e.g. see Table 4 in Akwa et al. (2012)). Besides, the prototypes under operational conditions will be immersed in the atmospheric boundary layer. Due to the multitude of possible geometries of the rotors number assembly and of different inflow conditions, it is not possible to reproduce all the different configurations in the wind tunnel. Therefore, a general situation has been tested in the wind tunnel whereas numerical simulations have been used to investigate the behaviour under a greater number of different wind flow conditions.

All the experimental tests have been carried out in the wind tunnel of the Department of Civil, Chemical and Environmental Engineering of the University of Genoa, which is a closed-loop subsonic circuit wind tunnel for aerodynamic and civil experiments. The wind tunnel has two different test sections, both with a cross-section of 1.7×1.35 m^2. The former is immediately after the convergent. The latter, used to carry out the present tests, is at the end of the working section, whose length is 8.8 m altogether. Fig. 2(a) shows the structure of the wind tunnel and the position of the two test sections.

A physical model at scale 1:12 of the complete wind turbine module with rotor and stators has been realized in aluminium (rotor) and wood (stators), as shown in Figs. 1(b) and 2(b). The rotor has been used only to evaluate the aerodynamic load on the rotor shaft, which is not shown in this paper.

The single stage model has been delimited by two circular end plates above and below it with a diameter equal to $1.7 \times R_e$ (Fig. 2(b)). Kubo et al. (1989) have shown that, when the diameter of the end plates is smaller than about 8 times the diameter of a circular cylinder, the flow becomes three-dimensional. Thus, in the